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OPTICS AND OPTO-ELECTRONICS SYSTEMS

Supplemental Grant Number DAAG29-85-K-0073

Robert W. Boyd and G. Michael Morris

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SCIENTIFIC PERSONNEL SUPPORTED BY THIS PROJECT

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Wayne R. Tompkin
Daniel J. Gauthier
Paul Narum

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Exact Theory of Pump Wave Propagation and its Effect on Degenerate Four-Wave Mixing in Saturable Absorbing Media, M. T. Gruneisen, A. L. Gaeta, and R. W. Boyd, J. Opt. Soc. Am., B 2, 1117, 1985.

Suppression of Amplified Spontaneous Emission by the Four-Wave Mixing Process, M. S. Malcuit, D. J. Gauthier, and R. W. Boyd, Phys. Rev. Lett., 55, 1086, 1985.

Saturated Absorption and Degenerate Four-Wave Mixing in Nd^{3+} Beta'' Alumina, R. W. Boyd, M. T. Gruneisen, P. Narum, D. J. Simkin, B. Dunn, and X. Yang, Opt. Lett. 11, 162, 1986.

Nonlinear Optical Interactions in Fluorescein-Doped Boric Acid Glass, M. A. Kramer, W. R. Tompkin, and R. W. Boyd, Phys. Rev. A, 34, 2026, 1986.

Simple, Compact, High-Performance, Permanent Magnet Faraday Isclator, D. J. Gauthier, P. Narum, and R. W. Boyd, Opt. Lett. 11, 623, 1986.

Instabilities in Four-Wave Mixing, R. W. Boyd, A. L. Gaeta, M. S. Malcuit, and P. Narum, SPIE Proceedings 667, 156, 1986.

Interferometric Measurement of Large Thermal Nonlinear Index in MBBA, D. J. Kinzer and G. M. Morris, Appl. Opt. 25, 1335, 1986.

Competition Between Amplified Spontaneous Emission and the Four-Wave Mixing Process, R. W. Boyd, M. S. Malcuit, and D. J. Gauthier, Phys. Rev. A 36, 4, 1987.

Observation of Deterministic Chaos in a Self-Pumped Phase Conjugate Mirror D. J. Gauthier, P. Narum, and R. W. Boyd, Phys. Rev. Lett. 58, 16, 1987.

Nonlinear Optical Properties of Lead-Tin Fluorophosphate Glass Containing Acridine Dyes, W. R. Tompkin, R. W. Boyd, D. W. Hall, and P. A. Tick, J. Opt. Soc. Am., B, 4, 1030, 1987.

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Population Pulsations and the Dynamic Stark Effect, R. W. Boyd and M. Sargent III, J. Opt. Soc. Am. B, 5, 1, 1988.

Instabilities in Laser Beams Counterpropagating through a Brillouin Active Medium, P. Narum, M. D. Skeldon, A. L. Gaeta, and R. W. Boyd, J. Opt. Soc. Am. B, 5, 623, 1988.

Passive One-Way Aberration Correction Using Four-wave Mixing, K. R. MacDonald, W. R. Tompkin, and R. W. Boyd, Opt. Lett. 13, 485, 1988.

Quantum Theory of Rabi Sideband Generation by Forward Four-Wave Mixing, G. S. Agarwal and R. W. Boyd, Phys. Rev. A. 38, 4019, 1988.

Polarization Instabilities of Counterpropagating Laser Beams in Sodium Vapor, D. J. Gauthier, M. S. Malcuit, and R. W. Boyd, Phys. Rev. Lett. 61, 1827, 1988.

Bandpass Filtering in Barium Titanate, L. Pugliese and G. M. Morris, Appl. Opt. 27, 4535, 1988.

Time Reversal of Berry's Topological Phase by Optical Phase Conjugation, W. R. Tompkin, M. S. Malcuit, R. W. Boyd, and R. Y. Chiao, in review.

Vector Phase Conjugation and Beam Combining by Multiwave Optical Mixing, R. W. Boyd, K. R. MacDonald, and M. S. Malcuit, Proc. of the SPIE, in press.

Computer-Generated Holography in Photorefractive Materials, L. Pugliese and G. Michael Morris, in review.

SUMMARY OF RESEARCH FINDINGS

This report describes the results of a research program entitled Optics and Opto-electronics Systems. The research was conducted by Professors Robert W. Boyd and G. Michael Morris of the University of Rochester's Institute of Optics. Professor Boyd's research involved the development characteristics and analysis of new nonlinear optical materials and nonlinear optical interactions. The primary application was new techniques for use in optical phase conjugation. Professor Morris's contribution was studies of nonlinear optical techniques for real time image processing. His work involved studies of real-time image correlation, nonlinear optical properties of liquid crystal compounds, and spatial resolution of nonlinear optical materials.

This research program was very successful and resulted in the publication of 20 papers in refereed scientific journals. We summarize our results by reproducing the abstracts of our published work.

Exact Theory of Pump-wave Propagation and its Effect
on Degenerate Four-wave Mixing in Saturable-absorbing media
M. T. Gruneisen, A. L. A. L. Gaeta, R. W. Boyd

An analytic solution for the intensity distribution of two counterpropagating pump waves within a saturable absorber is derived. From this distribution, the spatial variation of the nonlinear absorption and coupling constants that appear in the coupled-amplitude equations for the probe and the signal (i.e., conjugate) waves are determined. These coupled-amplitude equations are solved numerically in a noniterative manner, leading to a prediction for the phase-conjugate reflectivity. The results of the exact theory are compared with those of previously published theories. It is found that at large values of the input-pump intensities, the predicted phase-conjugate reflectivity is larger when pump-absorption effects are included in the theory.

Suppression of Amplified Spontaneous Emission
by the Four-Wave Mixing Process
M. S. Malcuit, D. J. Gauthier, and R. W. Boyd

Two-photon-resonant excitation of the sodium $3d$ level can lead to the generation of new frequencies either by amplified spontaneous emission at the $3d \rightarrow 3p$ transition frequency or by a resonantly enhanced four-wave mixing process. Competition between these two processes has been observed. The four-wave mixing process can suppress amplified spontaneous emission by preventing the excitation of the $3d$ level due to an interference between two different pathways connecting the ground ($3s$) and $3d$ states.

Saturated Absorption and Degenerate Four-wave Mixing in Nd^{3} beta" Alumina

R. W. Boyd, M. T. Gruneisen, P. Narum,
D. J. Simkin, G. Dunn, and D. L. Yang

Nd^{3} beta" alumina is one of a family of potentially useful nonlinear-optical materials based on rare-earth ions substituted in a beta" alumina host. The saturation intensity of Nd^{3} beta" alumina has been measured to be in the range 16 to 35 kW cm^{-2}. Phase conjugation by degenerate four-wave mixing has been demonstrated, and the phase-conjugate reflectivity has been measured as a function of both laser wavelength and intensity.

Nonlinear-optical Interactions in Fluorescein-doped Boric Acid Glass

M. A. Kramer, W. R. Tompkin, and R. W. Boyd

Fluorescein-doped boric acid glass is a material characterized by an extremely low saturation intensity of ≃15 mWcm^{-2} and a nonlinear susceptibility $\chi^{(3)}$ as large as ≃1 esu. The saturated absorption of this material is shown both theoretically and experimentally to depend on the state of polarization of the saturating beam, even though the unsaturated absorption is polarization insensitive. Pahse-conjugation reflectivities as large as 0.6% have been obtained through use of degenerate four-wave mixing in this material. These measured reflectivities are in good agreement with the predictions of a theory that includes the effects of excited-state absorption and grating washout. In addition, two-beam coupling due to the nonlinearity of saturabel absorption has been demonstrated in this material. The magnitude of the coupling is maximized by inducing a frequency shift between the two beams of ≃0.1 Hz.

Simple, Compact, High-Performance Permanent-Magnet Faraday Isolator

D. J. Gauthier, P. Narum, and R. W. boyd

This design of a Faraday isolator that uses a short glass rotator rod and produces highly uniform rotation across its clear aperture is presented. The rotator rod is 19.5 mm long, and at a wavelength of 633 nm the rotation angle is 45 deg and the isolation ratio is >45 dB.

Instabilities in Four-Wave Mixing

R. W. Boyd, A. L. Gaeta, D. J. Gauthier, M. S. Malcuit, and P. Narum

Recent research on instabiliites in the four-wave mixing process is summarized. The four-wave mixing process can cause a laser beam to become unstable to the growth of new frequency components as the beam propagates through a nonlinear medium. Similar instabilities can occur in more complicated optical systems such as lasers and bistable optical devices. The nature of the instability is very different for nonlinearities resulting from one- and two-photon resonances in the susceptibility describing four-wave mixing. The four-wave mixing process can lead to chaotic behavior in a self pumped phase conjugate mirror.

Interferometric Measurement of Large Thermal Nonlinear Index in MBBA

D. J. Kinzer and G. M. Morris

A Twyman-Green interferometer is used to study a large optical nonlinearity, believed to be thermal in origin, in the nematic liquid crystal MBBA. Fringe shifts arising from laser-induced heating of the nematic layer are measured and compared to a solution of the heat equation. There is reasonalbe agreement between experiment and theory in the dependence of fringe shift on beam intensity and cell temperature.

Competition between Amplified Spontaneous Emission and the Four-Wave Mixing Process

R. W. Boyd, M. S. Malcuit, D. J. Gauthier, and K. Rzazewski

Competition between amplified spontaneous emission (ASE) and the four-wave-mixing (FWM) process has been observed under conditions of two-photon resonant excitation of the sodium 3*d* level. The nature of the competition is that the FWM process is able to prevent the occurrence of ASE, even though the gain of the ASE process calculated in the absence of competition effects is much larger than that of FWM. The ASE is suppressed because the fields generated by the FWM process create a new excitation pathway connecting the ground and 3*d* levels, and under quite general conditions this pathway interferes desctructively with that due solely to the applied laser field. These effects are modeled theoretically by solving perturbatively the density-matrix equations of the atomic system, thereby determining the population in the upper level and the nonlinear polarization of the medium. The coupling between the various optical fields due to the nonlinear polarization is described by coupled amplitude equations. The solution to these equations predicts that when the wave-vector mismatch is not too large the fields evolve spatially to reach steady-state values, and that the population excited to the 3*d* level by the total steady-state optical field is much smaller than that due to the incident laser field alone. We have observed experimentally the suppression of ASE by FWM and have observed that this suppression does not occur when the medium is excited with counterpropagating beams that cannot efficiently excite the FWM process. In addition, we have conducted a series of experiments that shows that the degree of suppression of ASE depends on the intensity and focusing characteristics of the incident laser as expected on the basis of our theoretical model.

Observation of Deterministic Chaos in a Self-Pumped Phase Conjugate Mirror

D. J. Gauthier, P. Narum and R. W. Boyd

Deterministic chaos in the intensity of the beam procduced by a barium titanate self-pumped phase-conjugate mirror has been observed. The correlation exponent of the strange attractor is found to depend on the crystal orientation and to lie within the range 1.2 to 2.4, and the order-two Renyi entropy is found to increase with increasing laser intensity and to be as large as 22 bits/sec. A standard model of self-pumped phase conjugation due to four-wave mixing has been generalized to include time dependence. This model predicts frequency shifts and chaotic behavior for the reflectivity.

Nonlinear-Optical Properties of Lead-tin Fluorophosphate Glass Containing Acridine Dyes

W. R. Tompkin, R. W. Boyd, D. W. Hall, and P. A. Tick

A new nonlinear-optical material based on lead-tin fluorophosphate glass doped with the organic dyes Acridine Orange and Acridine Yellow has been developed. These materials are saturable absorbers characterized y saturation intensities of '100 mW cm^{-2}, response times of '1 msec, and third-order nonlinear susceptibilities of '0.1 esu. The low melting temperature of the lead-tin fluorophosphate glass permits doping with many organic dyes without causing their decomposition.

Non-Frequency-Shifted Phase Conjugation by Brillouin-enhanced four-Wave Mixing

P. Narum and R. W. Boyd

We present a theoretical treatment of four-wave mixing in a Brillouin-active medium for the case in which the pump waves differ in frequency by approximately twice the Brillouin frequency shift of the medium and in which the probe-wave frequency is approximately the arithmetic mear of the frequencies of uthe two pump waves. Under these conditions, the conjugate wave produced by the four-wave mixing process has the desirable property of being at the same frequency as the probe. We derive the coupled amplitude equations describing this interaction. We solve these equations analytically in the limit of negligible pump depletion and find that large phase conjugate reflectivities are readily achievable. The coupled amplitude equations are solved numerically for the general case, and it is found that large power transfer from the pumps to the output wave is possible. The output wave is shown to abe a nearly perfect phase conjugate of the probe wave even far into the regime where pump depletion effects are important. Our formalism predicts the existence of a parametric instability in the propagation of the pump waves, but good performance is predicted before the onset of this instability.

Population Pulsations and the Dynamic Stark Effect

R. W. Boyd and Murray Sargent III

We present a theoretical description of the interaction of optical waves due to the resonant nonlinear response of an atomic system. We emphasize how the resonant nature of the nonlinear coupling is modified by the shifting of the pulsations in determining the nature of the nonlinear coupling. A general formalism is developed to treat these effects and is explicitly applied to several examples of current interest, including single-beam saturation spectroscopy, pump-probe saturation spectroscopy, modulation spectroscopy, degenerate four-wave mixing for phase conjugation, and instabilities in the beam propagation through resonant media.

Instabilities of Laser Beams Counterpropagating through a Brillouin-active Medium

P. Narum, A. L. Gaeta, M. D. Skeldon, and R. W. Boyd

Counterpropagating laser beams in a Brillouin-active medium are shown to become unstable to the growth of amplitude and phase fluctuations. Slightly above threshold, the nature of the instability is the temporal growth of sidemodes separated from the laser frequency by approximately the Brillouin frequency of the medium. This process leads toi sinusoidal oscillations of the intensities of the transmitted waves. At higher input intensities the system can become chaotic; many sidemodes are excited, and the transmitted fields fluctuate wildly. The origin of the Brillouin instability is the combined action of the gain of the standard stimulated Brillouin scattering (SBS) process and of the coupling of the waves due to multiwave mixing mediated by the electrostrictive interaction. The threshold for the instability is at least several times lower than the threshold of the standard SBS process involving a single pump beam.

Passive One-way Aberration Correction Using Four-wave Mixing

K. R. MacDonald, W. R. Tompkin, and R. W. Boyd

We have demonstrated a passive method for recovering an optical image that has been degraded by being passed through a thin phase-aberrating medium. This method relies on a point source situated near the object of interest to sample the aberration impressed upon the wave front. Degenerate four-wave mixing in fluorescein-doped boric acid glass was used to reconstruct the wave front.

Quantum Theory of Rabi Sideband Generation by Forward Four-Wave Mixing

G. S. Agarwal and R. W. Boyd

The predictions of a quantum mechanical theory of forward four-wave mixing in a homogeneously broadened system of two-level atoms are presented. In the limit of a very short interaction region, the predictions of this theory reproduce those of well known theories for the spontaneous emission spectrum of an atom in the presence of an intense laser field. More generally, the theory predicts how the emission spectrum is modified due to propagation effects for a medium of arbitrary length. For long propagation pathlengths, the emitted radiation can be quite intense and has a spectrum that is strongly peaked at the Rabi sidebands of the incident laser frequency. The theory shows that Rabi sideband generation in the forward direction can be understood as parametric amplification of weak radiation emitted spontaneously at the Rabi sidebands. The quantum noise that initiates the four-wave mixing process has contributions both from fluctuations in the incident vacuum radiation field and from fluctuations in the polarization of the atomic dipoles. Both contributions are important for the case of a radiatively broadened medium, although the material fluctuations make the dominant contribution for the case of a medium in which the broadening is largely collisional. Under certain conditions large amounts of squeezing in the radiated field is predicted.

Polarization Instabilities of Counterpropagating Laser Beams in Sodium Vapor

D. J. Gauthier, M. S. Malcuit, and R. W. Boyd

We have observed temporal instabilities in the polarization of counterpropagating laser beams in atomic sodium vapor. For intensities slightly above the instability threshold, the polarizations fluctuate periodically. For higher intensities, the fluctuations are chaotic and the system evolves on a strange attractor whose fractal dimension increases with increasing laser intensity.

Time Reversal of Berry's Topological Phase by Optical Phase Conjugation

W. R. Tompkin, M. S. Malcuit, R. W. Boyd, and R. Y. Chiao

We have examined experimentally the time-reversal properties of Berry's topological phase in one of its optical manifestations, Pancharatnam's phase, through use of optical phase conjugation. The time-reversal symmetry of the total optical system is broken by the nonreciprocal element, a Faraday rotator. Nevertheless, we found that the topological part of the phase acquired by an optical wave in passing through the system still respects time-reversal symmetry: it remains odd under time reversal.

Vector Phase Conjugation and Beam Combining by Multiwave Optical Mixing

R. W. Boyd, K. R. MacDonald, and M. S. Malcuit

This research presents a review of the various techniques for achieving vector phase conjugation and some results on a new method for laser beam combining based on multiwave optical mixing in atomic vapors.

Bandpass Filtering in Barium Titanate

L. Pugliese and G. M. Morris

Real-time spatial filtering is performed in $BaTiO_3$ using two different holographic geometries. In both geometries white light images of moderate intensity are used to filter selected portions of Fourier transform holograms written in the crystal. The result is a suppression of certain spatial frequencies in the reconstructed images. The geometries consist of a typical four-wave mixing arrangement and a new self-reading setup. In both geometries erase images are supplied by a commercial projection system. These arrangements permit one to generate and position spatial filters electronically, thereby avoiding the often difficult process of physical preparation and alignment of conventional spatial filters. Other image processing applications of the self-reading configuration are also discussed.

Computer-Generated Holography in Photorefractive Materials

L. Pugliese and G. Michael Morris

Computer-generated holograms allow holographic information storage without the need to record an actual interference pattern produced by combining two or more coherent beams. We describe a method to create and reconstruct computer-generated holograms in photorefractive materials. In our method computer-generated Fourier transform holograms are imaged into a $BaTiO_3$ craystal using either spatially coherent or incoherent light. Intensity variations in the image produce a proportional index change in teh $BaTiO_3$ by the photorefractive effect. By illuminating the resulting phase hologram with a coherent beam the holographic image is reconstructed. Reconstructions obtained using the coherent-writing geometry are found to have higher diffraction efficiency in general than those produced in the incoherent system. Characteristics of reconstrucions from both systems depend upon imaging system f-number, crystal orientation, hologram-grating-vector direction, and read-beam polarization.